Relationship Between Alfvenic Fluctuations and Heavy Ion Heating in the Cusp at 1 Re

Victoria Coffey[1], Michael Chandler[1], Nagendra Singh[2]

[1]NASA Marshall Space Flight Center, [2]University of Alabama in Huntsville

Abstract

We look at the effect of heavy ion heating from their coupling with observed broadband (BB-ELF) emissions. These wave fluctuations are common to many regions of the ionosphere and magnetosphere and have been described as spatial turbulence of dispersive Alfven waves (DAW) with short perpendicular wavelengths. With Polar passing through the cusp at 1 Re in the Spring of 1996, we show the correlation of their wave power with mass-resolved O^+ derived heating rates. This relationship led to the study of the coupling of the thermal O^+ ions and these bursty electric fields. We demonstrate the role of these measurements in the suggestion of DAW and stochastic ion heating and the observed density cavity characteristics.

1. Introduction

On a moving spacecraft, short wavelength dispersive Alfven Waves (DAW) are Doppler shifted and observed as ELF electromagnetic noise (BB-ELF) over a broad frequency range (typically below 220 Hz). In this paper we follow the plasma properties of the O^+ ion energization with the power in the BBELF waves. In a typical cusp pass of 5100 km, the Polar spacecraft observes BBELF waves coincident with ion energization. Figure 1 shows a typical spectrogram from the Polar Plasma Wave Instrument (PWI) of the BBELF noise in the bottom panel along with the Polar TIDE O^+ energization in the top panel. Figure 2 shows a polar contour of the ubiquitous nature of BBELF from PWI. Figure 3 shows the moments during a typical cusp pass with the density cavity occurring during the temperature increase.
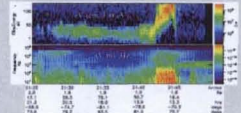

Figure 1. Top panel: Polar TIDE energy/time spectrogram showing typical cusp ion O^+ energy increase from 21:42 to 21:45 in the cusp. Bottom panel: PWI observations of BBELF emissions at this same time.
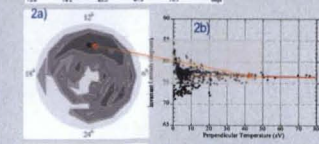

Figure 2a) Contours of PWI electric PSD at 10 Hz frequency band 2b) Invariant latitude as a function of O^+ perpendicular temperature. The mean invariant latitude is approximately 76.8°.
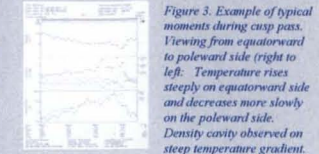

Figure 3. Example of typical moments during cusp pass. Viewing from equatorward to poleward side (right to left). Temperature rises steeply on equatorward side and decreases more slowly on the poleward side. Density cavity observed on steep temperature gradient.

2. Ion Heating and Stochastic Ion Heating Rates

The correlation between ion energization and the BBELF power is well known. Figure 4 demonstrates this strong correlation as observed from Polar for the dayside cusp passes at 5100 km. This data consists of » 6000 data points with the O^+ perpendicular temperatures averaged within each PSD bin. The profile at the 5.62 Hz frequency band is similar for the other frequencies profiles in the PWI BBELF range with no structure seen at the gyrofrequency in frequency profiles. The temperatures as a function of the sum of the PSD from 5.6 to 311 kHz is also shown. A threshold is suggested between 10^{-9} and 10^{-8} $V^2/m^2/Hz$ and is analogous to the threshold of 10^{-9} $V^2/m^2/Hz$ at ~1500 km found by Knudsen [1998] during Freja apogee passes.

Although limited in sampling period, the comparison of three different heating rate calculations from measurements for stochastic ion acceleration for a static electric field are shown in Figure 5. Each of the three rates are obtained using Polar measurements. All assume local heating as observed in Section 3 of this paper.
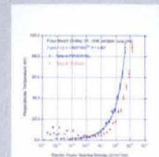

Figure 4. Strong correlation (R=0.997) of averaged O^+ perpendicular temperature as a function of the 5.6 Hz PSD (blue) and the sum of the frequency bands (red).

Heating Rate (blue) = $dT/dt = V_p \cdot E_x$ Staciewicz [2000]

Heating Rate (red) = $dT/dt = \frac{(T_{pf} - T_{po})}{(\frac{\Delta l}{V_{SC}})_{perp}} = \frac{(T_{pf} - T_{po})}{(V_{SC} \cdot \Delta l)_{perp}}$

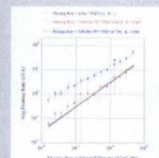Heating Rate (black) = $\dot{W}_\perp (eV) = \frac{q}{2m} \psi$

Figure 5. Comparison of heating rate calculations as a function of PSD. TIDE/PWI cusp heating rate measurements (red) and (blue). Compared to the heating rate for stochastic ion acceleration (black).

3. Observations, Particles and Fields

For the dayside cusp, BBELF and ion energization is often coincident with large currents and large electric fields perp. to the local magnetic field. Figure 6 shows the Polar/EFI perpendicular electric field (red) coincident with the increase in TIDE O^+ perpendicular temperature (blue) for May 12, 1996. Observations of continuous 90°O^+ ion conics during this same time period indicate that a local ion heating mechanism is in effect (Figure 7).
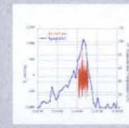

Figure 6. Polar TIDE and EFI observations showing O^+ perp. temperature increase coincident with large perpendicular electric field, E_x.
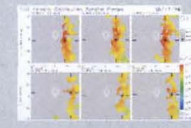

Figure 7. TIDE velocity distributions of 90 ° ion conics during full time period.

4. Observations, Fields

When the perpendicular scale of DAW waves become comparable to the ion gyroradius the wave becomes dispersive and interacts strongly with the particles. Again, these short wavelength DAW are Doppler shifted and observed as ELF electromagnetic noise or BB-ELF. One method of heating the ions when $\omega < \omega_i$ can be explained by stochastic ion heating by these short perpendicular wavelength electrostatic waves [Chaston 2005]. Here we look at signatures of one typical cusp pass provided by Polar/TIDE and EFI and determine through data analysis if the fields are Alfvenic and if the ion heating can be explained by the stochastic process. The ratio of $\delta E/\delta B$ was constructed for spacecraft frequencies below ω_{O^+}. The fluctuations are greater than the Alfven speed of » 10^4 km/s. Figure 8 shows the power spectrum of δE and δB and their ratio as a function of frequency and wavelength in the spacecraft frame.
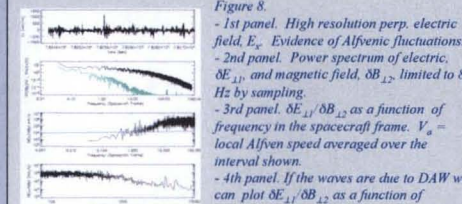

Figure 8.
- 1st panel. High resolution perp. electric field, E_x. Evidence of Alfvenic fluctuations.
- 2nd panel. Power spectrum of electric, $\delta E_{\perp 1}$, and magnetic field, $\delta B_{\perp 2}$, limited to 8 Hz by sampling.
- 3rd panel. $\delta E_{\perp 1}/\delta B_{\perp 2}$ as a function of frequency in the spacecraft frame. V_a = local Alfven speed averaged over the interval shown.
- 4th panel. If the waves are due to DAW we can plot $\delta E_{\perp 1}/\delta B_{\perp 2}$ as a function of wavelength. Vs = spacecraft velocity.

Figure 9 shows the perpendicular electric fields with Alfvenic fluctuations and the calculation of $\chi = dE/dx \cdot (\omega_O^+ B_o)^{-1} > 1$. The observed electric field gradients do exceed the stochastic ion heating mechanism criteria, $\chi > 1$, for assumed wavelengths of 1921 meters (approximately $4\rho_O^+$ with 100 eV at 5100 km) and lower.
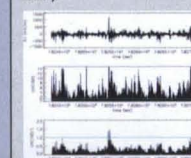

Figure 9. Panel A. High resolution perpendicular electric field, E_x, for May12. Evidence of Alfvenic fluctuations.

Panel B,C. Calculation of electric field gradients reveals $\chi > 1$ for two assumed wavelengths scales; 100 meters (B) and 1921 meters(C). (O^+ 100 eV Larmor radius = 473 meters.)

5. Observations, Density Structures

It was suggested by Chaston [2006] that the width of the density cavities can increase due to the production of Alfven waves on the transverse density gradients. Over the narrow cusp passes, we averaged the density cavities, $(n_0 - n)/n_0$ and the width of the density cavities for each PSD bin.. Figure 10 suggests an increase in the density depth from 30% - 60% with the increase in PSD and Figure 11 also suggests an increase in the average width of the density cavity from 168 km to 294 km with the increase in PSD.
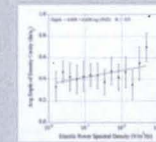

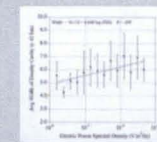*Figure 10. Average density depth as a function of PSD.*

Figure 11. Average width of density cavity as a function of PSD.

6. Summary

Cusp observations are often coincident with strong perpendicular electric field gradients and continuous 90° conics over the narrow cusp passes. We begin by showing that the power observed from BB-ELF, now thought to be Doppler-shifted short-wavelength DAW, is consistent with stochastic ion heating by turbulent fields. Analysis for a particular Polar pass show Alfvenic fluctuations evident in the perpendicular electric field and that the $\delta E/\delta B$ fluctuations are greater than the local averaged Alfven speed and so the electromagnetic fluctuations are suggestive of Alfven waves. Data analysis shows that the stochastic heating mechanism may be in effect for the cusp at 5100 km. The stochastic heating criteria, $\chi > 1$, is met for scale lengths appropriate for O^+. Although limited by the sampling period, analysis on the density cavitation shows vertical depths ranging from 30-60% and horizontal density cavity widths of ~ 200 km.

7. References

Lotko, JASTP, 2007; Chang, JGR, 1986; Chaston, JGR, 2005; Chaston, JGR, 2006